

The Temperature and Pressure Dependencies of Propagation Characteristics for Premixed Laminar Ethanol-Air Flames

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Abstract: Laminar burning velocity is strongly dependent on mixture characteristics, e.g. initial temperature, pressure and equivalence ratio. In this work, spherically expanding laminar premixed flames, freely propagating from a spark ignition source in initially quiescent ethanol-air mixtures, have been imaged and then the laminar burning velocities were obtained at initial temperatures of 358 K to 500K, pressure of 0.1 to 0.2 MPa and equivalence ratio of 0.7 to 1.4. The measured results and literature data on ethanol laminar burning velocities were accumulated, to analyze the effects of initial temperature and pressure on the propagation characteristics of laminar ethanol-air flames. A correlation in the form of $u_l = u_{l0} (T_u/T_{u0})^{\alpha T} (P_u/P_{u0})^{\beta P}$ was proposed, and validated over much wide temperature, pressure and equivalence ratio ranges. The global activation temperatures were determined in terms of the laminar burning mass flux for ethanol-air flames. And the Zel'dovich numbers were estimated as well. The dependencies of global activation temperature and Zel'dovich number on initial mixture pressure, temperature and equivalence ratio were explored. Additionally, an alternative correlation of laminar burning velocities, from the view of theoretical arguments, was proposed on the basis of the determined ethanol-air laminar mass burning flux. Good agreements were obtained in its comparison with the literature data.

Keywords: Ethanol, laminar burning velocity, burning mass flux, Zel'dovich numbers, activation temperature.

INTRODUCTION

In response to the environmental problems related to oil consumption and the associated emissions of CO₂ and other pollutants, many politicians, researchers and others advocated for the use of alternative fuels to replace conventional fossil fuels. Ethanol is a renewable energy since it can be commonly produced from bio-mass [1], such as softwoods, sugar cane and maize. And it has been identified as offering an attractive potential to improve air quality when used to replace conventional gasoline or diesel in engines because of its good anti-knock characteristics and the reduction of CO and unburned hydrocarbon (HC) emissions [2]. Considering its excellent performances in engine and renewable feature, ethanol is being regarded as one of the most promising alternative fuels for engines.

A key characteristic of a fuel is its laminar burning velocity, which is fundamentally important in regard to predicting its performance in combustion system, as well as in regard to design of engine. The studies relevant to its determination have been extensively implemented in the last fifty years. The tested fuels have covered most of hydrocarbon fuels,

e.g. methane [3, 4] hydrogen [5], iso-octane [6], tert-butanol [7] etc. The first systematic measurement for laminar ethanol-air flames was initiated by Gülder [8] in 1982. He conducted an experiment for premixed ethanol-air mixtures in a closed combustion bomb, and obtained the laminar burning velocities in the range of 0.1-0.8 MPa pressures, 300-500K temperatures and equivalence ratios from 0.7 to 1.4. In his study, the laminar burning velocities were obtained from the measured flame growth rate by using six ionization probes installed in the combustion bomb, and the effect of stretch, which was imposed on the flame, have been ignored. Hereafter, Egolfopoulos *et al.* [9] implemented a counterflow ethanol flames measurement at atmospheric pressure in 1992, and determined the laminar burning velocities between 363 and 453K.

The bursting attentions on ethanol laminar flames occurred in the beginning of the 21st century, because of the approved attraction of ethanol to improve engine performances. Holley *et al.* [10] conducted an experimental measurement and chemical kinetics computation to determine this fundamental parameter for premixed ethanol-air laminar flame in 2004. Subsequently, Farrell [11], Liao [12], Bradley [13], Konnov [14] and Eisazadeh-Far [15] with their co-workers, made experiments at the extended mixture temperatures, pressures or equivalence ratios ranges, and reported some literature data for gaseous ethanol mixtures in air. However, the obtained results still presented somewhat apparent scatterings.

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As we know, laminar burning velocity is a strongly dependent parameter of mixture features, e.g. initial temperature, pressure and mixture equivalence ratio. And generally, this fundamental parameter is determined at standard condition, for example, atmospheric pressure and initial temperature of 298 K, or relatively low temperature and pressure, primarily owing to some difficulties in experimental setups and measurements. However, in most practical applications, initial pressure and temperature of the mixture are often higher than the standard values. Therefore, it is very important to quantify the effects of pressure and temperature on these fundamental parameters [14]. Shown in Table 1 is an overview on the temperature and pressure dependencies of laminar burning velocities for ethanol-air flames. We note that, Liao *et al.* [12] and Konnov *et al.* [14] proposed the correlations in the form of $u_l = u_{l0}(T_u/T_{u0})^{\alpha_T}$. Their particular attentions were paid on the effect of initial temperature on laminar burning velocities. Gülder [8] gave his empirical formula in the form of $u_l = u_{l0}(T_u/T_{u0})^{\alpha_T}(P_u/P_{u0})^{\beta_P}$ and validated the temperature and pressure power exponent coefficients over the range of initial temperatures from 300 to 500K at the pressure of 0.8 MPa. In his study, α_T was a constant of 1.75, and a piecewise function was obtained to describe the power exponent β_P against mixture equivalence ratio. Hereafter, Bradley *et al.* [13] made their experimental measurements from 0.1 up to 1.4 MPa, and Eisazadeh-Far *et al.* [15] extended the measured temperatures up to 650K. They summarized some empirical correlations to formulize the effects of pressure and temperature on laminar burning velocities as well. Generally speaking, all empirical expressions mentioned above were valuable for most of practical applications. However, their major disadvantages were their limited validation ranges for initial temperatures, pressures, and equivalence ratios. For instance, the pressure dependence have not been investigated by Liao *et al.* [12] and Konnov *et al.* [14]; the equations proposed by Bradley *et al.* [13] and Eisazadeh-Far *et al.* [15] were only validated within equivalence ratios from 0.8 to 1.2; the study of Gülder[8]

showed apparent scatterings against the latest literature data. Moreover, others important propagation characteristics for laminar ethanol-air flames, such as the global activation flame temperatures and Zel'dovich numbers, have still scarcely been studied. It is therefore necessary to make a comprehensive study on the laminar ethanol-air flames dependencies, over much wider temperatures, pressures, and equivalence ratios ranges, for much better understanding, and modeling combustion process of ethanol.

The experimental method used herein was the expanding flame imaging and processing technique, which have been well-established to deduce flame speed, flame stretch, as well as laminar burning velocity from the recorded history of flame kernel development. The major objective of this paper, therefore, was to provide some improved expressions for laminar ethanol-air flames, as well as to study their temperature and pressure dependencies. The validations were implemented for these proposed empirical equations over much wider mixture conditions, through the comparison of present measurement with the latest literature data. Furthermore, on the basis of the asymptotic theory of flame structure, the expressions for global activation flame temperature, Zel'dovich numbers have been deduced, and their dependencies on mixture parameters were explored as well.

EXPERIMENTAL SETUP AND DATA PROCESSING

The spherically expanding flame method in a constant volume combustion bomb have been extensively used to measure laminar burning velocities of gaseous and liquid fuels. Detailed description of this method and the associated experimental uncertainties could be found elsewhere [12]. Herein, some important features were outlined in the following. In the present experiment, a stainless steel bomb with an inside size of 108x108x135mm was employed. Two sides of the bomb were transparent to make the inside observable and provide the optical access for flame imaging. Two electric heaters were mounted at the bomb wall to preheat the gas and a closed-loop controlling system have been used to ensure the gas temperature at a desired value. The experimental procedures involved five steps primarily. Firstly, the bomb

Table 1. Summary of the Investigation on Laminar Burning Velocities for Ethanol-air Flames

Authors	α_T^a	β_P^b	Temperature (K)	Pressure (MPa)	Equivalence Ratio (ϕ) ^c	Experimental Technique	Year
Gülder	O	O	300-500	0.1-0.8	0.7-1.4	combustion bomb	1982
Egolfopoulos <i>et al.</i>	X	X	363-453	0.1	0.6-1.8	counter-flow flame	1992
Farrell <i>et al.</i>	X	X	450	0.3	0.55-1.3	combustion bomb	2004
Liao <i>et al.</i>	O	X ^d	358-480	0.1	0.7-1.4	combustion bomb	2007
Bradley <i>et al.</i>	O	O	300-393	0.1-1.4	0.8-1.2	combustion bomb	2009
Konnov <i>et al.</i>	O	X	298-358	0.1	0.65-1.55	heat flux method	2011
Eisazadeh-Far <i>et al.</i>	O	O	300-650	0.1-0.5	0.8-1.1	cylindrical vessel	2011

^{a,b}: letters of 'O' and 'X' indicate the parameters of α_T and β_P are available or not respectively, where α_T and β_P are the parameters in Equation 7.

^c: if the exponents of α_T or β_P available, these values give its relevant validated range of equivalence ratio.

^d: the exponent of β_P is reproduced from Gülder [8].

would be preheated to a value above the desired temperature and then left to cool. Following, the combustion bomb was evacuated and flushed with air to remove residuals from previous experiment and evacuated again. Thirdly, the liquid fuel was injected into the combustion chamber using a Gas Tight syringe, at a pressure close to vacuum. Subsequently, dried air was introduced into chamber and the perforated plate started to move manually, to enhance the motion of fuel in air for the homogenous distributions of mixture density and temperature. In the present experiment, as all measured temperatures were beyond the boiling point of ethanol, the injected liquid ethanol could be evaporated rapidly at a pressure close to vacuum. Finally, the ignition occurred when the gas temperature attained to the desired temperature and the motion of perforated plate have been suspended for at least five minutes, to ensure combustible mixture at quiescent condition. Meanwhile, the history of the shape and size of the developing flame kernel was recorded synchronously by a REDLAKE HG-100K high-speed CCD camera, operating at 5000 pictures per second with a schlieren optical system.

The laminar burning velocity could be deduced from the well-established expanding flames method as described in some literatures [12]. Given in follows was a sketch about this method. Herein, the stretched flame speed, S_n , is derived from the flame radius versus the elapsed time t as,

$$S_n = \frac{dr_u}{dt} \quad (1)$$

where flame size r_u is determined from the schlieren flame area directly.

And the flame stretch, α , of a flame front is then given by,

$$\alpha = \frac{1}{A} \frac{dA}{dt} \quad (2)$$

where A indicates the flame front area. In the case of outwardly propagating spherical flame, it can be determined as,

$$\alpha = \frac{1}{A} \frac{dA}{dt} = \frac{2}{r_u} \frac{dr_u}{dt} = \frac{2}{r_u} S_n \quad (3)$$

The unstretched flame speed, S_l , is obtained from ,

$$S_l - S_n = L_b \alpha \quad (4)$$

Thereby, the unstretched laminar burning velocity, u_l , yields as,

$$u_l = \rho_b S_l / \rho_u \quad (5)$$

Where ρ_u is the density of the unburned and ρ_b that of the burned gas, which can be determined from quasi-dimensional two-zone combustion model [16]. The standard error of estimation can be found in [6].

RESULTS AND DISCUSSIONS

Laminar burning velocities of ethanol-air flames were measured using the spherically expanding method within the

ranges of 358-500 K, equivalence ratios from 0.7 to 1.4 and at pressure of 0.1 and 0.2 MPa. As mentioned above, following a series of procedures about flame processing, the values of flame area, flame radius, and subsequently, flame speed, flame stretch rate, the density of burned and unburned mixture, and laminar burning velocities of ethanol flames could be derived methodically. Plotted in Fig. (1) were the measured laminar burning velocities for ethanol-air flame at 358K and atmospheric pressure, against mixture equivalence ratio. This figure plotted some literature data for comparison as well. Generally speaking, acceptable agreements have been achieved, and especially for lean and stoichiometric fuel-air mixtures. Compared to the data of Bradley *et al.* [13] (2009), Konnov *et al.* [14] (2011) and Eisazadeh-Far *et al.* [15] (2011), it was obvious that our measurements were comparable, and the best agreements appeared in the comparison with the experiment made by Bradley *et al.* Compared to the results of Bradley *et al.* and Konnov *et al.*, some apparent deviations were also displayed for flames of equivalence ratio bigger than 1.3. It is possible due to the small dimensions of the vessel used. However, these discrepancies were within an acceptable zone against those measured by Gülder and Egolfopoulos *et al.* We can see that, for ethanol-air flame, at normal pressure of 0.1 MPa and temperature of 358K, the maximum burning velocity was approximately between 58 cm/s and 61cm/s. And on the basis of all the available literature data, the unstretched laminar burning velocities could be formulized as a function of equivalence ratio by means of the least-squares method, as

$$u_{l0} / (cm.s^{-1}) = -175.02\phi^2 + 391.1\phi - 162.5 \quad (6)$$

Where the subscript ‘o’ indicated the reference conditions, i.e., 358K and 0.1 MPa in this work. As large amounts of data have been introduced to the empirical equation development, we can obviously find that, the present equation showed a better agreement with all measured data, compared to that previous version, $u_{l0} = -207.07\phi^2 + 450.1\phi - 189.71$ [11], as plotted in Fig. (1) as well. The maximum burning velocity of Eq.6 was about at the equivalence ratio of 1.07, corresponding to the measured value of 58.1 cm/s. In Fig. (1), a highlighted zone was illustrated to show the $\pm 5\%$ deviations of Eq.6. Note that, most of experimental measurements appeared within this zone. And only a spot of points were exceptions, e.g. the measurements of Bradley *et al.* Konnov *et al.* and the present experiment at equivalence ratio of 0.9, and our measurement for mixture of 1.4. Moreover, a comprehensive comparison have been conducted between the present measured laminar burning velocities and other literature data for mixtures at 358K, and 453K at 0.2 MPa, as presented in Fig. (2) and Fig. (3) respectively. We note that, the present experimental results were fully comparable with those made by Bradley *et al.* while the predictions of Eisazadeh-Far *et al.*, [15] were obviously bigger than the measured values, in which apparent discrepancies have been observed in the comparison between the empirical prediction and the experimental data, when mixture equivalence ratios were in a higher range. This was due to the empirical solution of Eisazadeh-Far *et al.*, was validated only within a comparatively narrow equivalence ratio range.

As we know, laminar burning velocity is a strongly dependent function of mixture characteristics, such as initial temperature, pressure and mixture equivalence ratio. More often, these dependencies could be generally expressed as a simple power law correlations of nondimensional temperature (T_u/T_{u0}) and nondimensional pressure (P_u/P_{u0}), at the datum conditions, as

$$u_l = u_{l0} (T_u/T_{u0})^{\alpha_T} (P_u/P_{u0})^{\beta_P} \quad (7)$$

Where α_T and β_P were the temperature and pressure exponents respectively.

Note that, Eq.7 could also be rewritten as,

$$\log(u_l/u_{l0}) = \alpha_T \log(T_u/T_{u0}) + \beta_P \log(P_u/P_{u0}) \quad (8)$$

Obviously, it is not hard to determine the parameters of α_T and β_P , by means of the least-squares analyses of $\log(u_l/u_{l0})$ vs. $\log(T_u/T_{u0})$ and $\log(u_l/u_{l0})$ vs. $\log(P_u/P_{u0})$ respectively. Shown in Fig. (4) were two selections about the determinations of α_T and β_P . We note that, the linear relationship was much stronger in the plots of $\log(u_l/u_{l0})$ vs. $\log(T_u/T_{u0})$ than in that of $\log(u_l/u_{l0})$ vs.

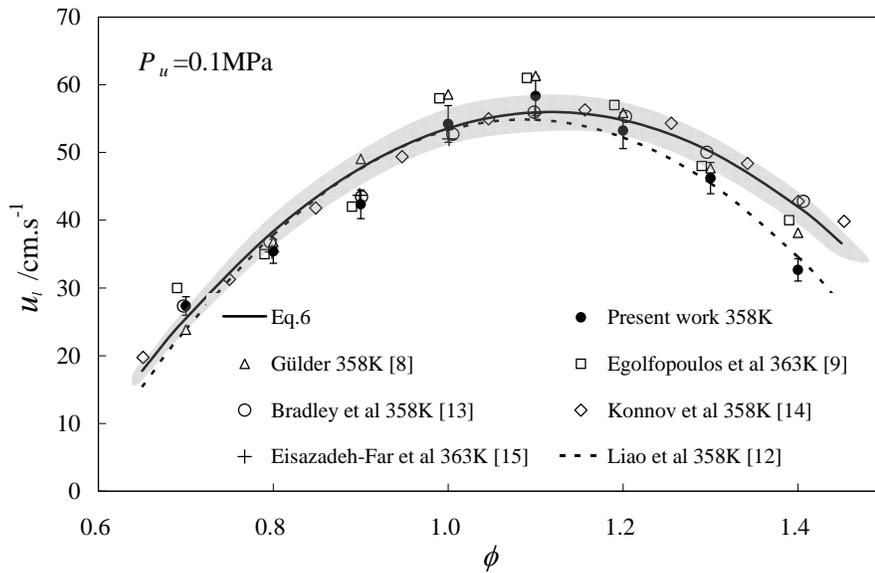


Fig. (1). Laminar burning velocities for ethanol-air flames at 358K and 0.1 MPa, where experimental values shown by symbols, the solid curve obtained from Eq.6, the dotted curve obtained from computation of Liao *et al.* [12]. The shaded area indicates the zone of $\pm 5\%$ deviations for Eq.6 predictions (some experimental symbols have been displaced slightly on the x-axis to improve clarity).

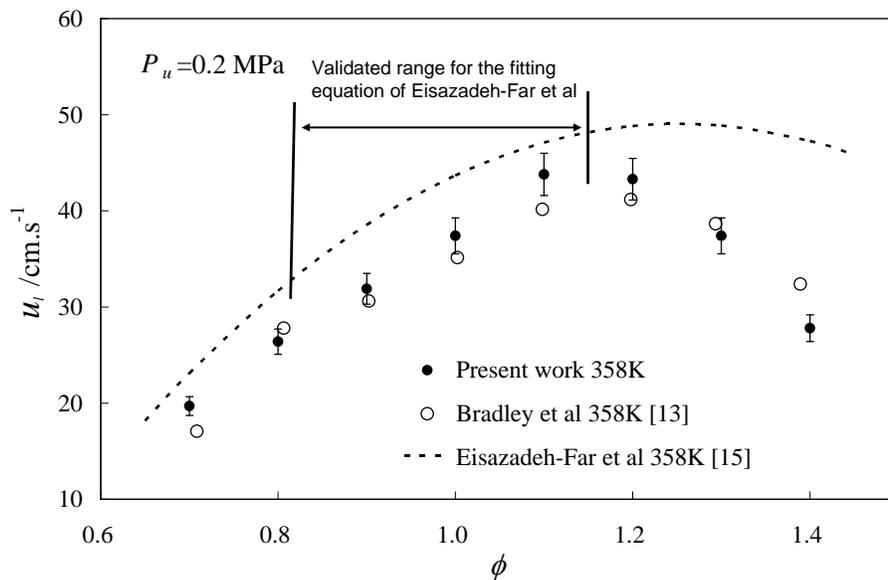


Fig. (2). Laminar burning velocities for ethanol-air flames at 358K and 0.2 MPa, where experimental values shown by symbols, and the dashed curve is obtained from the fitting equation of Eisazadeh-Far *et al.* [15] (which was validated within the equivalence ratio ranging from 0.8 to 1.1, and some experimental symbols have been displaced slightly on the x-axis to improve clarity).

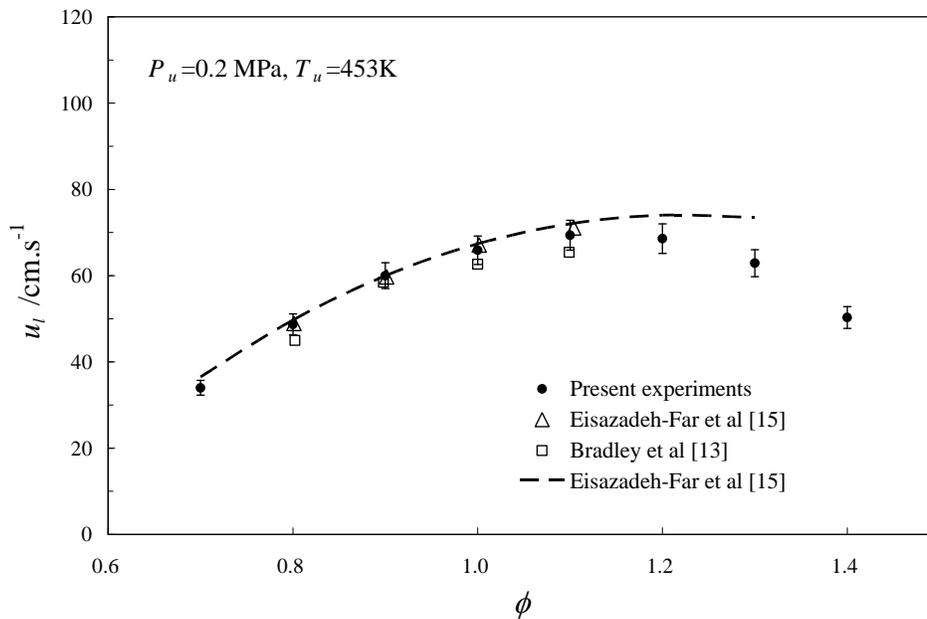


Fig. (3). Laminar burning velocities for ethanol-air flames at 453K and 0.2 MPa. Experimental values shown by symbols. Computed values shown by dotted and dashed curves respectively. (Some experimental symbols have been displaced slightly on the x-axis to improve clarity).

$\log(P_u/P_{u0})$. In which, most experimental measurements were scattered around the fitted line closely. Thereby it is easy to get the value of α_T , as shown in Fig. (4A). However, more obvious scatterings have been observed in the plots of $\log(u_l/u_{l0})$ vs. $\log(P_u/P_{u0})$. Fig. (4B) also revealed that the present measurements have shown a comparable slope of $\log(u_l/u_{l0})$ against $\log(P_u/P_{u0})$ with that of Bradley *et al.* [13]. Actually, it is very difficult to find some physical meanings to this phenomenon, but similar research facilities and similar data procedures were the possible reasons. As these reasons could also be used to analyze the clustering behaviors for measurements of Eisazadeh-Far *et al.* [15] and Gülder [8]. In their studies, the laminar burning velocities were commonly derived from pressure rise histories. The experimental method was apparently different from the flame processing technique used by Bradley *et al.* [13] and the authors. Thereby, the pressure exponent β_p was also determined from the linear fitting among the measurements of present experiment and those of Bradley *et al.* Whilst, because the initial temperature showed much stronger influence on flame propagation than pressure ($\alpha_T \gg \beta_p$), weak variation in value of α_T have not brought a comparable statistical result as that of β_p . Fig. (5) showed the variations of α_T and β_p , against mixture equivalence ratio. On these bases, two generalized correlations have been summarized to quantify their dependencies on the equivalence ratio, as given in Eq.9 and Eq.10.

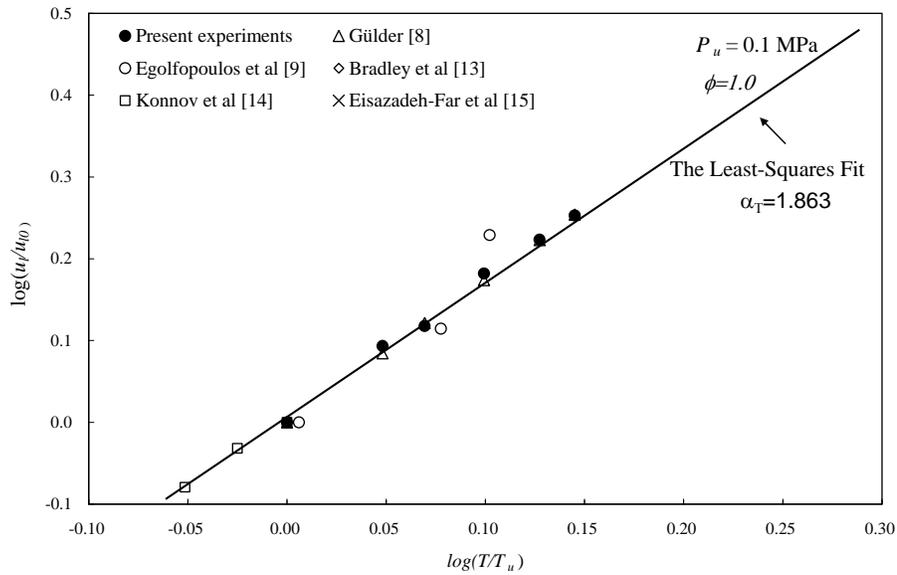
$$\alpha_T = 1.4738\phi^2 - 3.5786\phi + 3.8944 \quad (9)$$

$$\beta_p = -0.4094\phi^2 + 1.0147\phi - 0.9181 \quad (10)$$

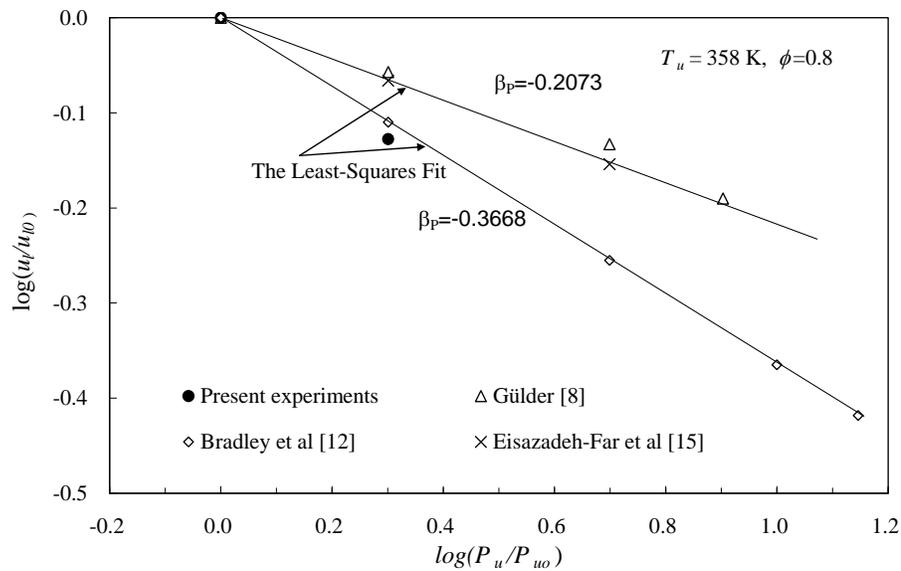
In Fig. (5), it is clear that α_T obtained by Bradley *et al.*, Eisazadeh-Far *et al.*, and Gülder showed stronger influence on the temperature exponent than those of Konnov *et al.* The reason for it is probably the lower temperature range of the experiments of Konnov *et al.* While for β_p , the variation of present values was nearly same as that of Bradley *et al.* Fig. (5) also showed two ± 0.3 and ± 0.15 deviation zones for α_T and β_p respectively. In general, all differences were not great. And the relative deviations of temperature exponent α_T were obviously smaller than those in β_p , although the temperature have presented greater dependence than pressure in the burning velocity of ethanol.

Eqs.7 through 10, have given a set of empirical expressions for the laminar burning velocities of ethanol-air mixture. In order to validate these empirical formulas, it is informative to let them make further comparisons with large amounts of literature data. Presented in Fig. (6) and Fig. (7) were some selective results, and good agreements have yielded among them. From these validations, we could confirm that, the proposed formulas could predict ethanol-air laminar burning velocities well, and their applicable ranges have been extended to some extent. For instance, their validated temperature range was from 300K to 600K and pressure from 0.1 to 1.4 MPa. certainly, one of the most important reasons was that the literature data introduced into the development of empirical equations have covered an extensive temperature and pressure ranges.

Theoretical analyses for stretched flames [17, 18] have reported that, the global activation energy E for the unstretched planar flame propagation could be determined on the basis of laminar burning velocities. Peters and Williams [19] have derived an asymptotic structure of the flame that introduced the inner layer temperature T^0 in the fuel consumption, and claimed that an apparent expression existed



A: $\log(u_1/u_{0})$ vs. $\log(T_u/T_{u0})$



B: $\log(u_1/u_{0})$ vs. $\log(P_u/P_{u0})$

Fig. (4). Determinations of temperature and pressure exponents of Eq.7.

within the activation temperature E/R and mass flux $(\rho_u u_1)$, given as,

$$\frac{E}{R} = 2T_b^2 \frac{d[\ln(\rho_u u_1)] / (g.cm^2.s^{-1})}{dT_b} \quad (11)$$

where R is the universal gas constant. Obviously, Eq.11 can also be rewritten as an alternative form,

$$\frac{E}{R} = - \frac{d2[\ln(\rho_u u_1)] / (g.cm^2.s^{-1})}{d(1/T_b)} \quad (12)$$

which indicated that the activation temperature E/R can be derived from the linear plot of $2 \ln(\rho_u u_1)$ against $1/T_b$ directly. That is to say, it is not hard to obtain the activation temperature E/R for a specific laminar planar flame when its laminar burning velocities were known. Shown in Fig. (8) were some plots of $2 \ln(\rho_u u_1)$ against $1/T_b$, where adiabatic flame temperature T_b was determined from chemical equilibrium computations. We can see that, E/R of ethanol-air mixtures showed a strong dependence on the initial pressure while it did not present apparent relationship against initial

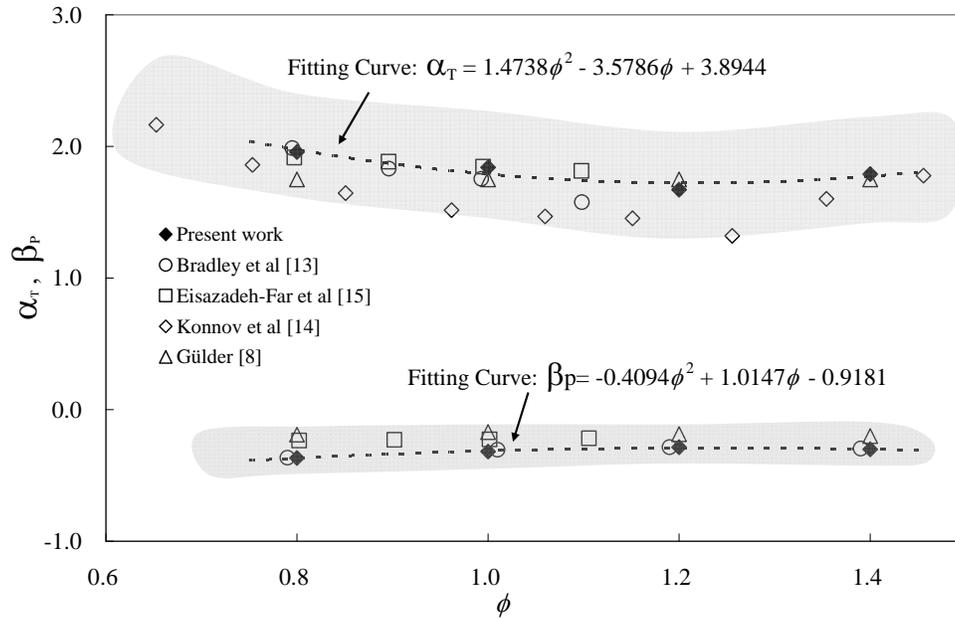


Fig. (5). Values of α_T and β_p exponents versus equivalence ratio of mixture, where the solid curve obtained from Eq.6, the dotted curves obtained from least-squares fitting of α_T and β_p in present study. The shaded area indicates the zone of ± 0.3 and ± 0.15 deviations for α_T and β_p respectively (some symbols have been displaced slightly on the x-axis to improve clarity).

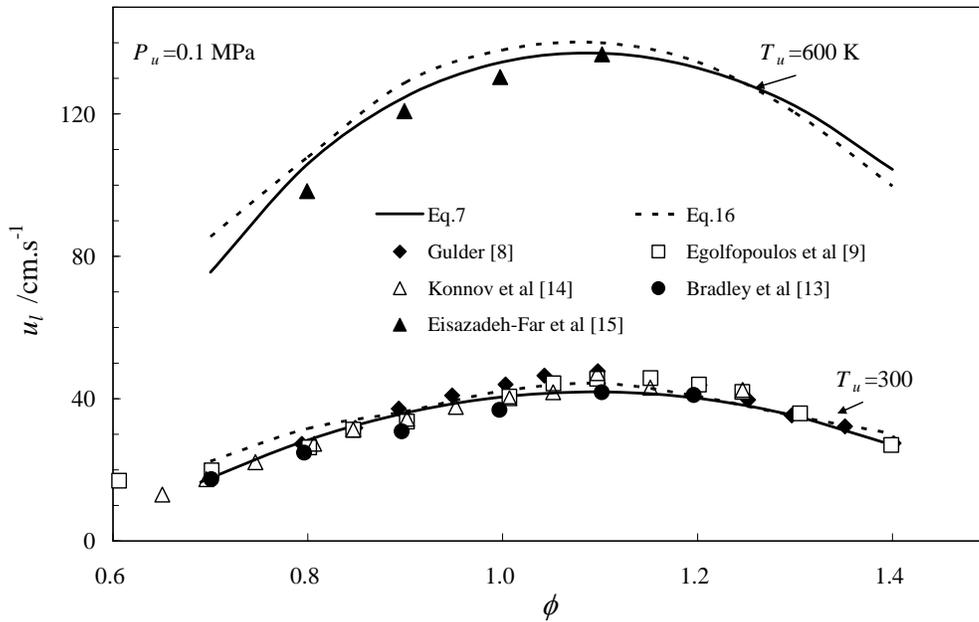


Fig. (6). Effect of initial temperature on the burning velocities for ethanol-air flames, where some symbols have been displaced slightly on the x-axis to improve clarity.

temperature, as same as those of methane-air [5] and methanol-air [20] flames. And the pressure dependence of E/R can be quantified as,

$$\frac{E}{R} = 985.66P_u + 17211 \quad (13)$$

where pressure P_u in MPa.

Generally, from Eq.11, we could also obtain,

$$\ln(\rho_u u_l) / (g.cm^2.s^{-1}) = -\frac{E}{2R} \frac{1}{T_b} + 0.5C \quad (14)$$

where C is the intercept value of fitting line of Eq.13 at $1/T_b = 0$, and

$$C = 10.764P_u^{0.2131} \quad (15)$$

Then an alternative form of u_l could be obtained as,

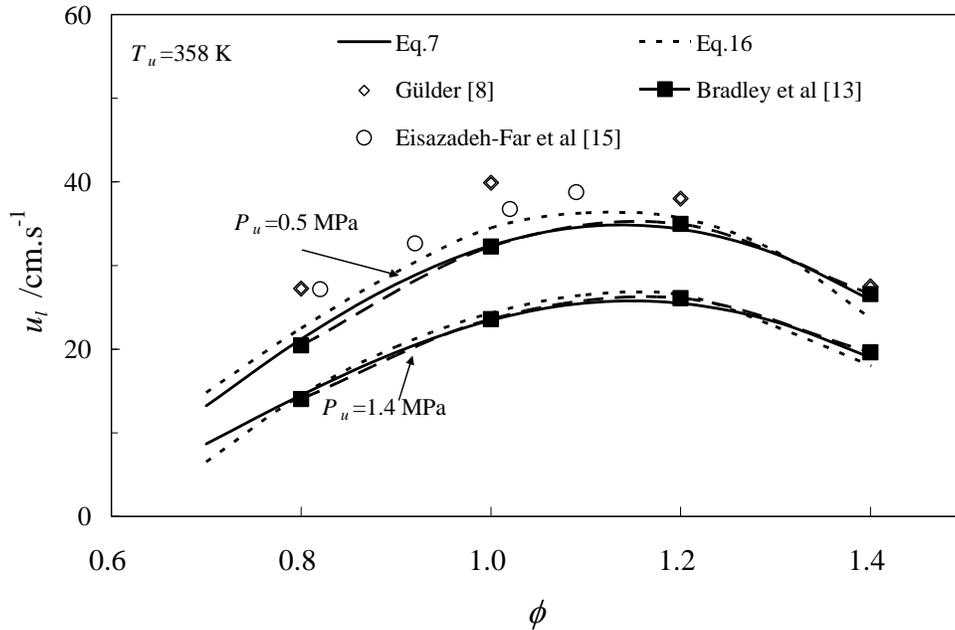


Fig. (7). Effect of pressure on the burning velocities for ethanol-air flames, where points obtained from experiments and curves from predictions, some symbols have been displaced slightly on the x-axis to improve clarity.

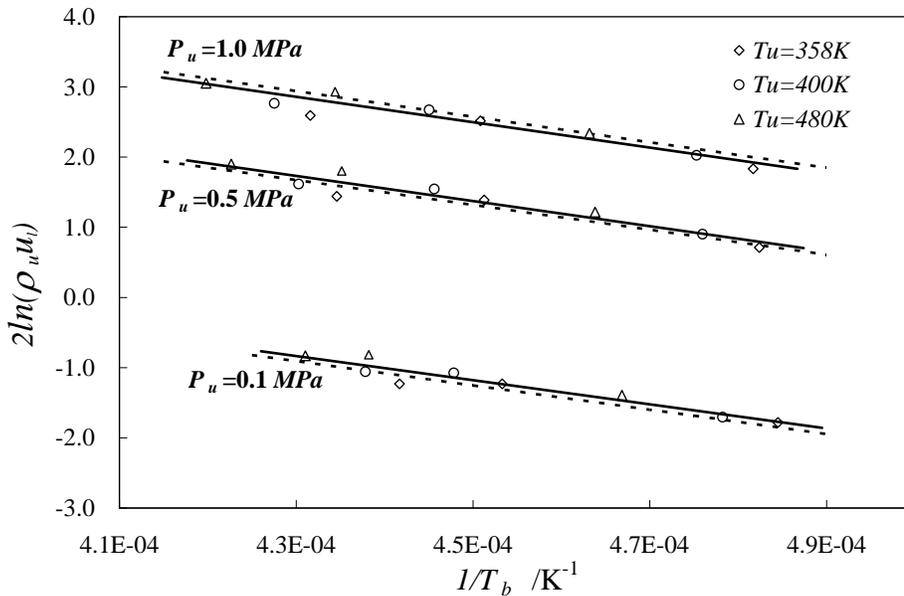


Fig. (8). Plots of $2\ln(\rho_u u_l)$ against $1/T_b$ for ethanol-air mixtures. Where solid lines are linear fits through the points obtained from Eqs.7, and dashed lines denote burning mass flux correlation of Eq.16, and some symbols have been displaced slightly on the x-axis to improve clarity.

$$u_l / (cm.s^{-1}) = \exp\left(-\frac{E}{2R T_b} \frac{1}{\rho_u} \frac{\exp(0.5C)}{(g.cm^{-3})}\right) \quad (16)$$

The calculated laminar burning velocities of Eq.16 have been plotted in Figs. (6) and (7) with dashed curves as well, to give its validation. We note that, no apparent discrepancy appeared in the comparison with experiments as well as with predictions of Eq.7.

The Zel'dovich number, Ze , is another important parameter for planar laminar flames. Theoretical analyses have

indicated that it can be determined from the active flame temperature [18].

$$Ze = \frac{E}{2RT_b^2} (T_b - T_u) \quad (17)$$

As we know, Ze is also a parameter to describe the sensitivity of chemical reactions to the variation of the maximum flame temperature and its reciprocal is strongly related to an effective dimensionless width of the reaction zone [21].

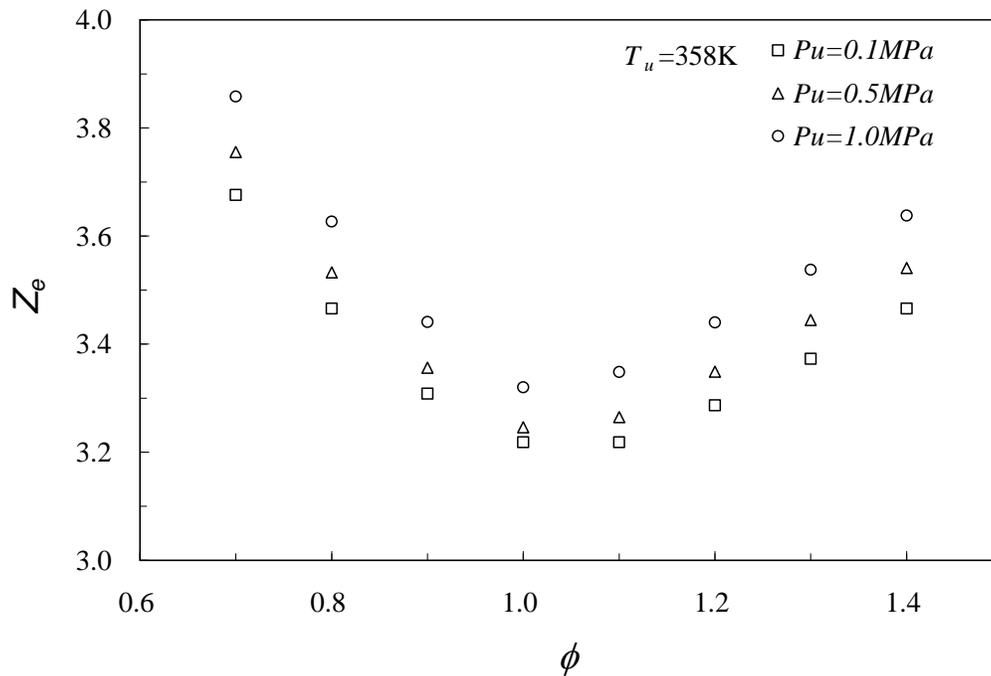


Fig. (9). Variations of Z_e with the equivalence ratio for ethanol-air flames at different pressure.

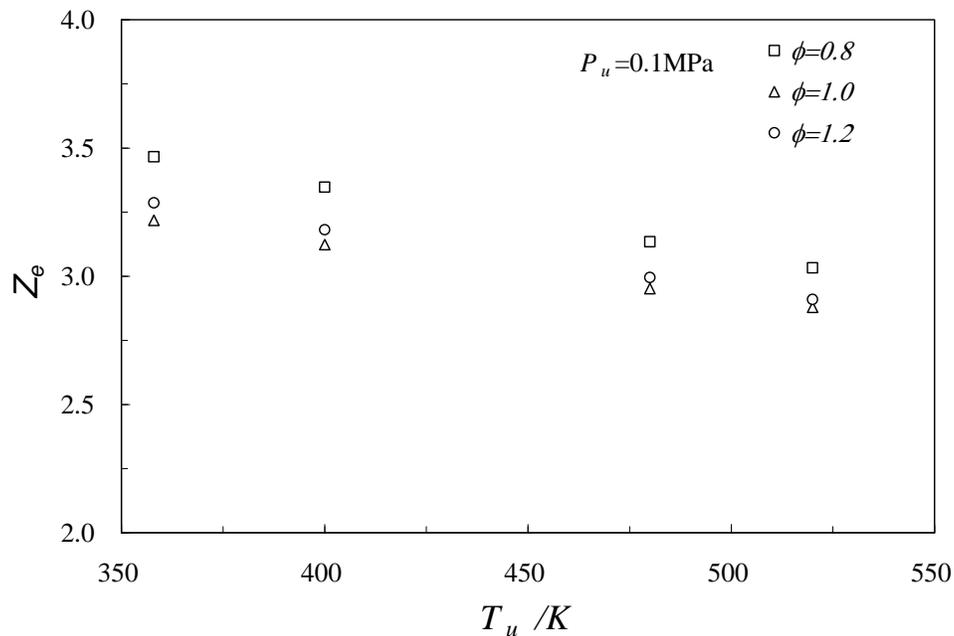


Fig. (10). Variations of Z_e with the preheated temperature for ethanol-air flames.

Shown in Figs. (9) and (10) were the variations of Z_e against the equivalence ratio for ethanol-air mixtures at different temperatures and pressures. As we can see, Z_e shows apparent dependencies on mixture equivalence ratio, temperature and pressure. Generally, the increase in pressure results in slight increase of Z_e , because of the increased inner flame temperature T^0 [21]. And Z_e decreases with the increase of initial temperature slightly, owing to a decreasing ratio of T_b to T_u . Additionally, Z_e attains its minimum at

near-stoichiometric condition, as the peak value of flame temperature T_b occurs herein.

CONCLUSIONS

In this paper, we conducted the experimental measurements for spherically expanding laminar flames of ethanol mixtures in air, from initial temperatures of 358 K to 500K, pressure of 0.1 to 0.2 MPa and equivalence ratio of 0.7 to 1.4, in a constant volume combustion bomb. The laminar

burning velocities were estimated using the spherically expanding flame method, and comprehensive comparisons and analyses were implemented within the present measurements and literature data, to deduce the temperature and pressure dependencies of laminar propagation characteristics. The major conclusions were as follows:

1. The present measurement showed comparable laminar burning velocities against the literature data for ethanol-air mixture, and an improved correlation has been proposed as $u_{l0} = -175.02\phi^2 + 391.1\phi - 162.5$ at 358K and 0.1 MPa.
2. By means of referencing literature data, a comprehensive analysis has been made to investigate the dependencies of the propagating characteristics of premixed ethanol flames in air, on initial temperature, pressure and equivalence ratio. An empirical formula in the function form of $u_l = u_{l0}(T_u/T_{u0})^{\alpha_T}(P_u/P_{u0})^{\beta_P}$ was obtained, and the pressure and temperature dependence exponents of α_T or β_P were formulized as functions of mixture equivalence ratio. These empirical expressions have been validated over much wider mixture conditions than all previous versions, in which temperature ranged from 300K to 600K, pressure from 0.1 up to 1.4 MPa and equivalence ratio from 0.7 to 1.4.
3. The expressions for mass burning flux, global activation temperature, and Zel'dovich numbers have been deduced on the basis of above power law formulas. And the pressure, temperature and equivalence ratio dependencies of active flame temperature and Zel'dovich numbers were studied. The global activation temperature of ethanol-air mixtures presents a strong dependence on the initial pressure, but weak relationship against initial temperature. Zel'dovich numbers increase with the increase of pressure and decreases with the increase of initial temperature.

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